Irradiance Observation of SMM, Spacelab 1, UARS, and ATLAS Experiments

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1 Detection of intrinsic solar variability on the total flux level was made using results from the first Active Radiometer Irradiance Monitor (ACRIM) experiment, launched on the Solar Maximum Mission (SMM) in early 1980. ACRIM 1, specifically y designed to start the high precision total solar irradiance database as part of the U.S. Climate Research Program, produced high precision results throughout the 9.75 years of the Solar Maximum Mission. The second ACRIM experiment was flown aboard the Space Shuttle as part of the NASA/ESA Spacelab 1 Mission in late 1983. Its primary function has been to provide a comparison with ACRIM 1 that could be used to relate its observations with future satellite solar monitors, should they and ACRIM 1 fail to overlap in time. The second ACRIM satellite solar monitoring experiment (ACRIM 11) has provided high precision total solar irradiance observations since its launch as part of the Upper Atmosphere Research Satellite (UARS) mission in late 1991 and continues at present. The shuttle ACRIM instrumentation has been flown on the ATLAS 1 and 2 missions in 1992 and 1993, providing comparisons with the UARS/ACRIM 11.

1. The SMM/ACRIM I experiment

'J he ACRIM 1 experiment 011 the Solar M aximum Mission provided the first unambiguous evidence of intrinsic total solar irradiance ('TSI) variability (Will son 1980) (see Figure 1). The first clear evidence was a 'J'S] 'dip' near 1980 day 100 (Willson *et. al. 1981*; Willson & Hudson 1981). This was caused by two large sunspot groups in an early stage of their evolution. The 'J'S] increases 011 either side of this dip were caused by faculae and plage surrounding the sunspots, which are the first and last components of the groups to be seen when the rotated onto and then off our side of the Sun, These two groups were identifiable for six solar rotations. On each successive rotation the ratio of facular area to sunspot area increased within these two groups. The impact of this can be clearly seen during the second dip near day 125 at whit}] time the effect of the sunspot area was significantly offset by the presence of relatively enhanced facular area (Willson 1982, 1984),

'J 'he solar cycle 'J'S] variation of about 0.1 % peak-to-peak can be clearly seen in Figure 2 which shows the entirety of the ACRIM 1 results for the 9.75 year mission, The occurrence of the 'J'S] minimum near the time of solar activity minimum (September 1986), as reckoned by the reversal of polarity of active regions, confirms the scalar cycle character of the TSI variation, (Willson & Hudson 1988, 1 991). One of the most important aspects of the discovery of a direct proportionality of 'J'S] and solar activity is that its direction is that required for solar forcing of climate change. This makes solar forcing a possible explanation of the 'Spörer, Maunder and 1 Dalton' climate Minima that occurred from the 14th through the 19th centuries, the 'Medieval Climate Maximum' of the 12th century (Eddy 1977; Anderson 1991).
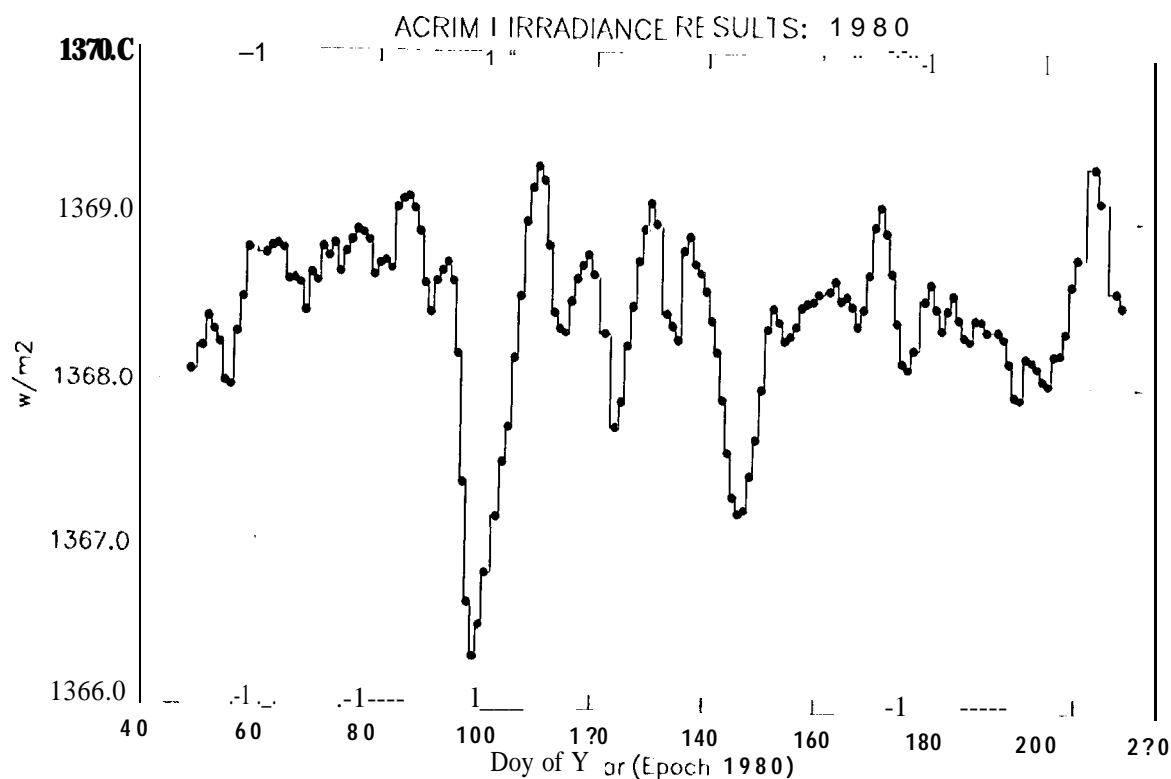
FIGURE 1, Results from the SMM/ACRIM experiment. Daily mean irradiance values are shown for the first six months of observation.
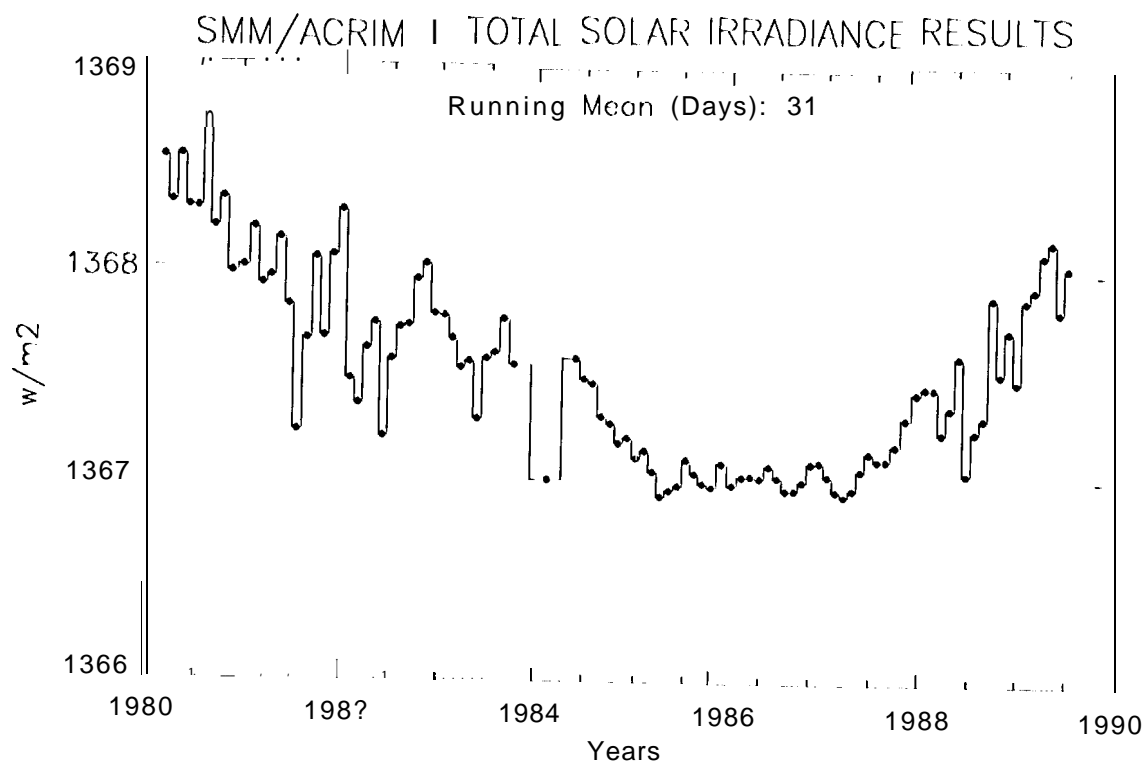

FIGURE 2. Results from the SMM/ACRIM 1 experiment. 31-clay running means smoothing is used to clarify the long term solar cycle trend.

RESULTS FROM THE UARS/ACRIM II EXPERIMENT
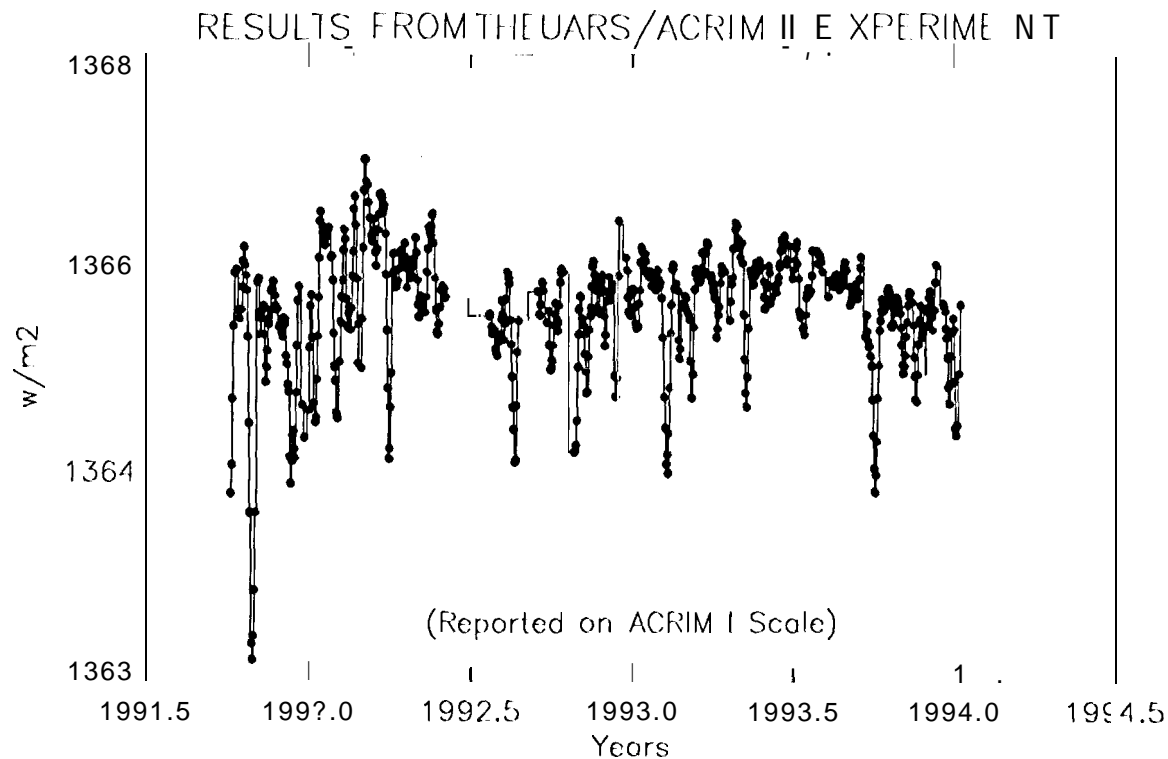

(Reported on ACRIM I Scale)

FIGURE 3. Results from the UARS/ACRIM II experiment. Daily mean irradiances are Shown reported on the scale Of the SMM/ACRIM I experiment (see Table]).

2. The UARS/ACRI M II experiment

The ACRIM 11 experiment, was launched in September 1 W], nearly two years after the demise of the Solar Maximum Mission, The results to date are shown in Figure 3. The launch delay of several years, caused by the Challenger accident, prevented the planned direct on-orbit comparisons between ACRI M] and 11. The importance of relating their results with precision through direct in-flight comparison cannot be understated since the inherent absolute accuracy of flight 'J'S] sensors is inadequate to sustain a useful long term database. Fortunately, we have been able to relate their results using the next best approach - by comparing both ACRIM 1 and ACRIM 11 with the contemporary observations by the Nimbus 7/ERB experi ment (Willson 1992). These comparisons are summarized in '-i'able 1 and shown in Figure 4. The benefit of having redundant 'J'S] monitoring experiments in place is dear from this, it has saved the continuity of the 'J'S] database. Without the benefit, of these overlapping comparisons, the relationship of future '1'S1 observations to the past could not be established with precision smaller than the solar cycle variation.

From Table] it can be seen that the ratio of ACRIM 1/ACRI M 11 can be established with an uncertainty of Icss that 5 ppm, assuming that only random errors affect the results. That this is not quite the case can be dearly seem in Figure 4. Systematic differences are seen in the plot of the ratio of Nimbus 7/ERB to ACRIM 1 in the form of an approximately sinusoids] variation nearly centered on their 9.45 year set of comparisons. Similarly, a systematic downward trend can be seen in the ratio of Nimbus 7/ERB to ACRIM II.

The causes of systematic differences between ACRI M and ERB are not known with certainty. They may be due to uncorrected thermal effects of the ERB instrumentation during the 1980-1990 period and to uncorrected degradation of ERB's sensitivity during
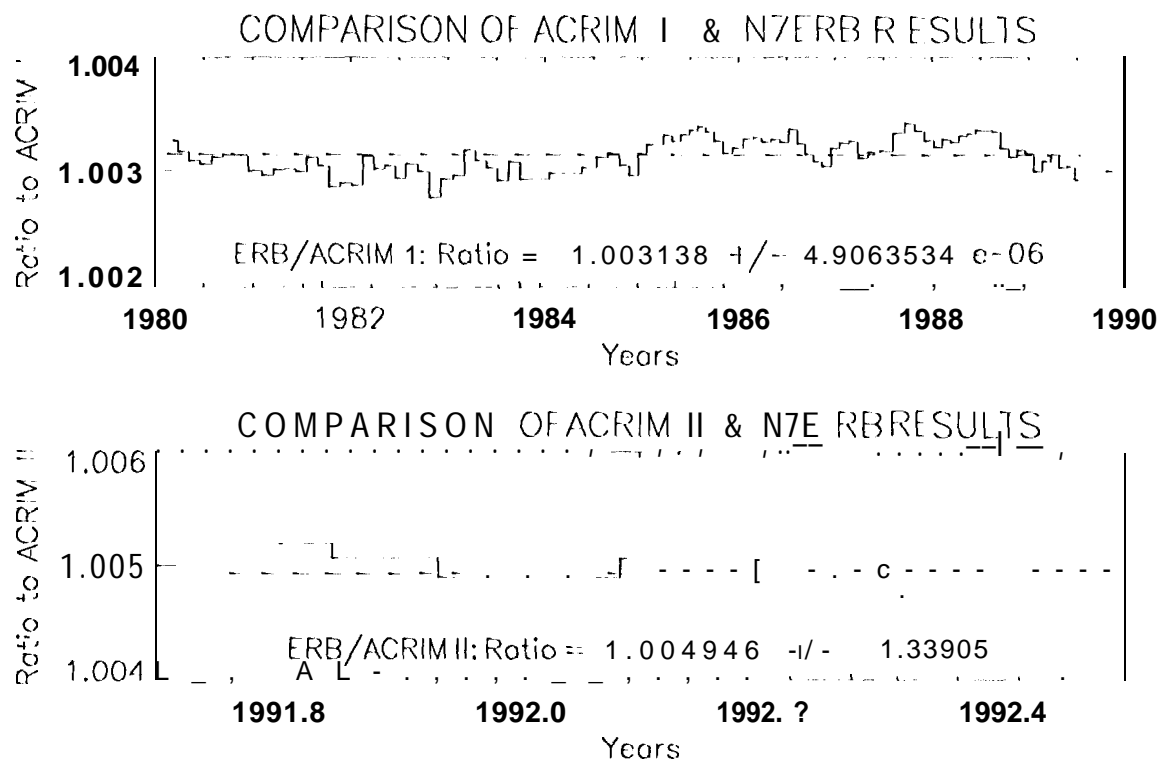
FIGURE **4,** Comparisons of SMM/ACRIM 1, UARS/ACRIM II and the Nimbus-7/ERB experiments. Results are shown as percentage variation.

1991-1992, Other evidences of shorter term ERB sensitivities to thermal effects can be observed in the results as divergences from the means in Figure 4 that significantly exceed the standard errors. The revision of the ERB results by Hoyt & Kyle (1 990) in which earlier database problems clue to pointing errors and thermal drifting were significantly reduced, concluded that residual thermal effects remained. A component of the systematic, differences is probably contributed by ACRIM I mis-performance as well, although by virtue of its more stable spacecraft thermal environment and much higher frequency of electrical self calibration, the contributions arc likely to be much smaller than ERB's.

Similar arguments implicate degradation of ERB's sensitivity as the source of the systematic downward trend relative to the ACRIM II results. By 1992 ERB had been in orbit more than 14 years, and although its total amount of direct solar exposure is only about 10'% of that of the ACRIM's per orbit, degradation s} iould be expected to be a factor in ERB results after that length of time. ERB has no degradation self-calibration capability, The ACRIM experiments have a multi-sensor degradation calibration ability that has demonstrated an inverse relationship of detector sensitivity and exposure to sol ar direct flux. 'J 'h erefore this type of relative trend suggests sensitivity degrad ation of the ERB, particularly during this period of exceptionally high solar activity when enhanced levels of high energy solar flux and particles are present, as the cause of the relative trend.

A more realistic estimate of the uncertainties of the ERB/ACRIM comparisons is being pursued through minimization of the systematic effects by modeling. Preliminary results indicate the residual uncertainty of the ACRIM I/ACRIM 11 ratio will be greater than the 2 ppm of 'l'able 1 and smaller than *50.*

3. Spacelab 1 /A CRIM, ATLAS/A CRIM and contemporary total **solar** irradiance experiments

Several TSI experiments have been concluded since launch of the UARS/ACRIM 11. The first was the ATLAS1/ACRIM in March 1992, the second the ATLAS2/ACRI M experiment in April, Two ESA TSI experiments, the PMOD (Brusa & Fröhlich 1972) and CROM (Crommelynck 1981) were included on the EURECA platform which was launched by the Shuttle in 1992 and retrieved in 1993 (see also Crommelynck *et. al. 1* 994; Romero *et. al. 1994).*

The shuttle based ACRIM experiment flown on the ATLAS 1 and 2 missions was also flown on the Spacelab 1 mission in 1 December 1983, The principal purpose of the shuttle ACRIM experiment was to make underflight comparisons with satellite 'J'S] monitoring experiments so that if the latter failed to overlap the precision of the database could be sustained through mutual inter comparisons with the shuttle ACRIM. The results of comparisons with satellite experiments is shown in Table 2. The Spacelab 1/ACRIM data was acquired during the SMM/ACRIM 1 mission. The ATLAS I & 2/ACRIM results were acquired during the UARS/ACRIM 11 experiment.

In the interest of understanding the reliability of the shuttle ACRIM results, the ACRI M 11 observations are scaled to ACRIM 1 as discussed previously, to facilitate comparison of Spat.clab 1 and A'J'] ,AS measurements. Sensor ACR502 was included in the ACRIM instrument on all three shuttle flights, the ACR504 on two. The weighted means are dominated by the A"J'] ,AS results because of their smaller uncertainties. This is caused by far smaller number of observations acquired during the Spacelab I mission when near total failure of the shuttle command-and-data system (I{, AU) occurred. The spread of the observations from the flights ($\pm$ 242 ppm for ACR502 and $\pm$ 152 ppm for ACR504) exceeds their statistical uncertainties by a large margin, indicating the clear intervention of sources of systematic error. It has been observed that the clean cavities of the A CRIM sensors provided for integration in each mission are contaminated when returned for recalibration after each flight. Contamination is believed to be the principal cause of the variation of results from flight-to-flight. The largest spread is between the ACR502 result of ATLAS1 and the other two, indicating that its second flight result could be anomalously high. This may be resolved by the A'J'] ,AS3/ACRI M experiment in late 1994.

It was hoped that the shuttle ACRIM series would be able to provide mission-to-mission precision better than 100 ppm instead of the approximately 200 ppm observed from the results to elate, While larger than expected, this bound of uncertainty is an order of magnitude superior to the absolute uncertainty of the current genera.tion of sensors, that operate at 'ambient temperature' and comparable to the absolute uncertainty of new cryogenic, 'J'S] sensors current under development. From this standpoint, the shuttle ACRIM experiment is a valuable insurer of the long term 'J'S] database, Should overlap of satellite 'J'S] monitoring experiments fail to occur in the future, the shuttle ACRIM comparisons could be used to sustain the TSI database precision at a useful level, even if less precisely than had been hoped.

The ESA EURECA platform was launched from the Shuttle in mid 1992 and retrieved about nine months later, Two 'J'S] monitors resided on the platform: the PMOD developed by Fröhlich (see Romero *et al.* 1994) and CROM developed by Crommelynck (see Crommelynck *et al.* 1994), A comparison of preliminary daily mean results obtained simultaneously by the PMOD, CROM and the UARS/ACRIM 11 experiments is shown in Figure 5 (Fröhlich 1993; Crommelynck 1993). The EURECA data shown begins shortly after its deployment. The results from all three experiments depict essentially
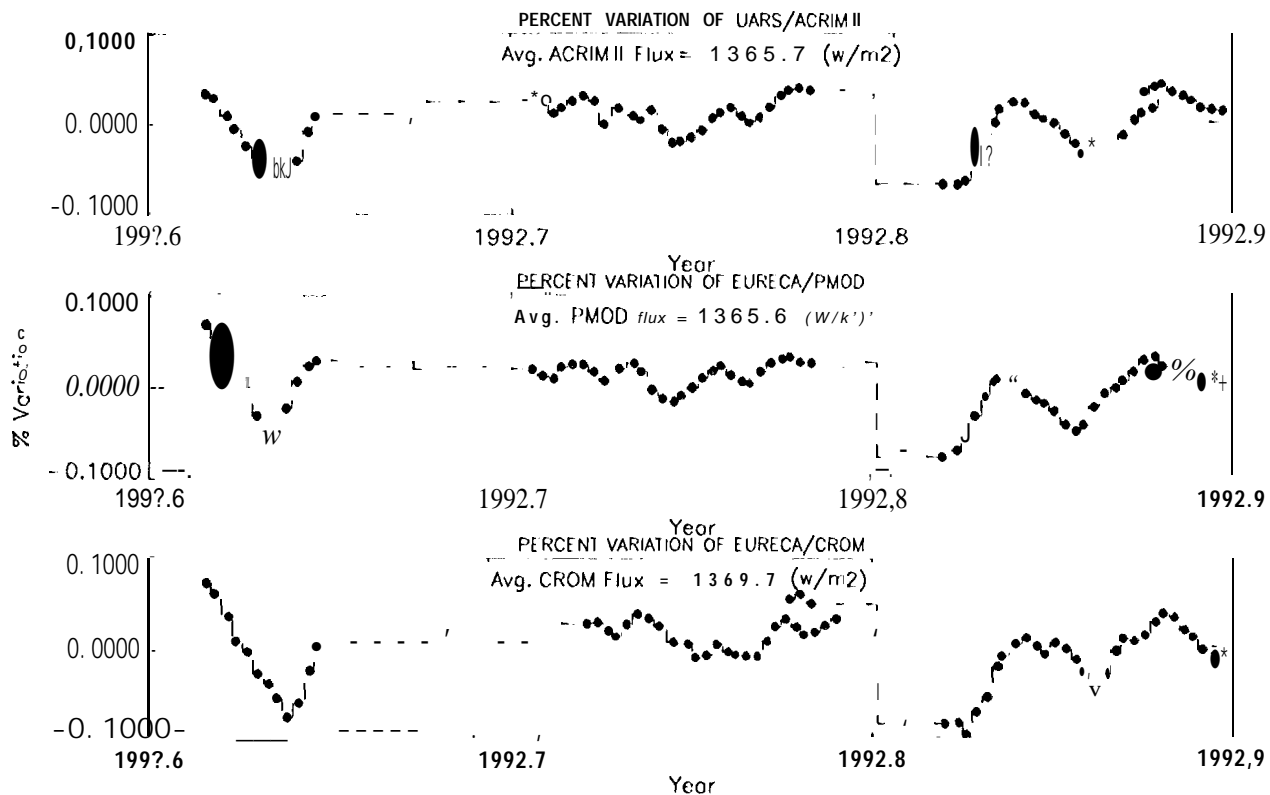
Figure 5. Comparisons of UARS/ACRIM 11 and the EURECA/PMOD and CROM results

the same principal TS] variations, including the 'sunspot deficit' effect of large sunspot groups in the early and late part of the period. The ACRIM 11 ant] I'MO]) results are most closely matched in both S1 units and the shape of their time series. The CROM utilizes a different operational mode and differs significantly in design from the PMOI) and ACRIM which probably explains the differences of shape of its time series. Both sets of EURECA results demonstrate higher initial decreases in flux, relative to ACRIM 11. This is probably due to high rates of degradation of their cavity absorbing surfaces in the early observations, a common feature of the initial] performance of 'J'S] sensors in space. The dashed lines of Figure 5 occur during periods when the UARS spacecraft was inoperational due to failure of the solar array's pointing mechanism and no simultaneous results were available for comparison.

These same data are presented in Figure 6 as the percentage difference from the UARS/ACRIM 11 results. A general downward trend in both the relative sets of results probably indicates uncorrected degradation in the PMOI) and CROM sensors accumulating w i t h exposure to solar high energy fluxes and particles. A high initial rate of relative decline for the CROM may indicate an accelerated initial degradation similar to that found in early results from the ACRIM experiments.

4. Summary

The TS] variability detected thus far is directly proportional to solar activity, as would be required by a solar forcing function for climate change that might have been responsible for the 'Maunder or Spörer climate Minima' of the 14th through the 17th centuries, and the 'Medieval Climate Maximum' of the 12th century, This implies the need t o exten d the high precision 'J'S] database indefinitel y wit]] maximum available precision

COMPARISON OF ACRIM II & PMOD RESULTS

PMO) - ACRIM II = 0.0084 +/-   0.00?0 **(% var)**

COMPARISON OF ACRIM II & CROM RESUL s
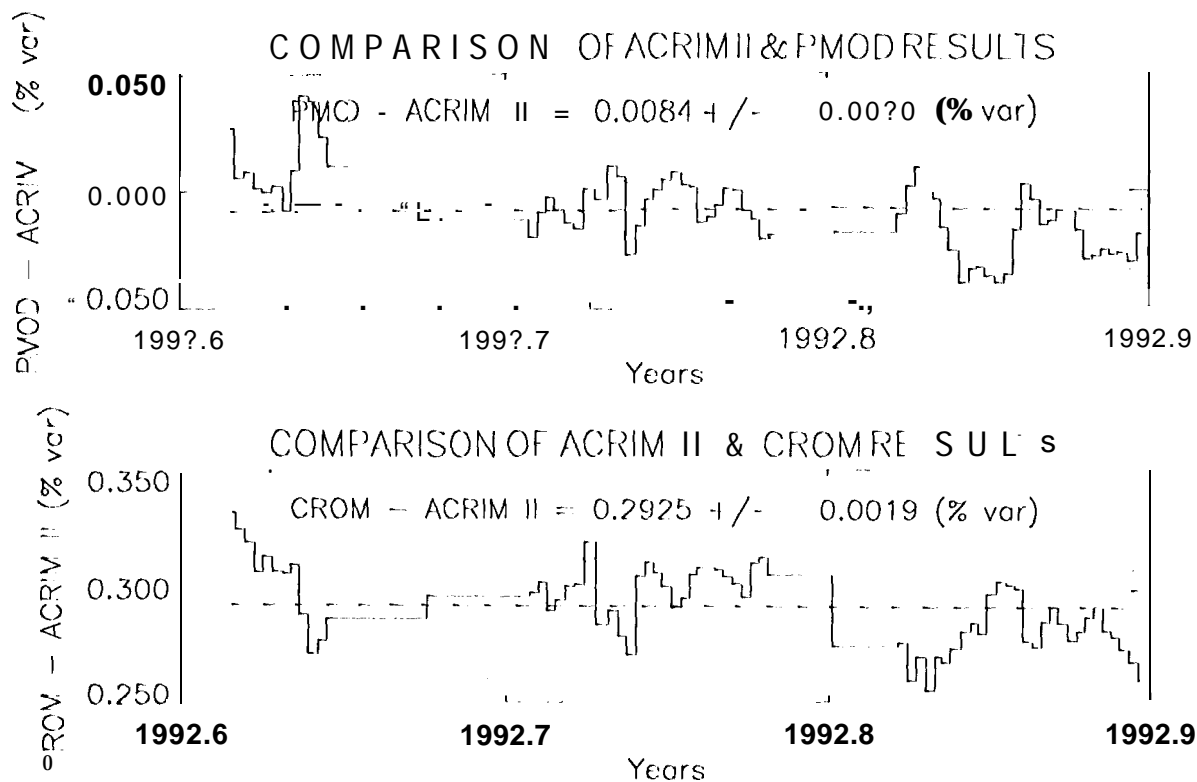
CROM - ACRIM II = 0.2925 +/-   0.0019 (% var)

FIGURE 6. Comparison of UARS/ACRIM 11 with PMOD and CROM results as percentage differences in time series,

to detect subtle, long term 'TSI variation. A careful measurement strategy that relates successive solar monitoring experiments at a precision level of the instrumentation will be required to sustain the database since the uncertainty of 'J'S] instrumentation on an absolute basis, even if operated at cryogenic temperatures, is inadequate for this purpose.

'J'here are presently no U ,S. experiments planned for the mid- to-late 1990's that have a high degree of probability for sustaining the 'J'S] database until deployment of the next ACRIM experiment as part the Mission to Planet Earth (on the Earth Observation System 'Chemistry' sate.llite in late 2002). If the current experimental scenario persists, the first high precision 'J'S] database will terminate in the late 1990's and the next will begin in 2002, with effectively no relationship between them of a sufficiently high precision to be useful for the long term study of either solar or climate variability.

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Table 1. Comparisons of SMM/ACRIM I and UARS/ACRIM II with Nimbus7/ERB experiment. Demonstration of the 'overlap strategy' capability for preserving the precision of the total solar irradiance database.

COMPARISONS	Ratio to ACRIM	Standard Error (1 sigma)	Number of Samples
Nimbus7/ERB - SMM/ACRIM I	1.003138	0.000004	2714
Nimbus7/ERB - SMM/ACRIM II	1.004946	0.000003	225
ACRIM I/ACRIM II (ERB Comparisons]	1.001802	0.000002	

Table 2. Results from the space shuttle ACRIM experiment on the Spacelab 1, ATLAS 1 AND ATLAS2 missions. Results are shown for ACR sensors 502 and 504 as their percentage variation relative to the radiation scale defined by the SMM/AC-RIM 1 instrument:

| Sensor: | ACR502 | Uncertainty (Note 1) | ACR504 | Uncertainty (Note 1) |
| | Average | +1- | Average | +/- |
Mission	(% var)	(% var)	(% var)	(% var)
Spacelab 1 (12/83)	0.3679	0.0098	0.4479	.0.0088
ATLAS 1 (3/92)	0.4164	0.0028	Not Flown	---
AT"LAS2 (4/93)	0.3680	0.0006	0.4174	0.0007
Wtd. Mean (All flights):	0.3701	0.0006	0.4176	0.0007
Variation (+/-):	0.0242		0.0152	
Wtd. Mean (ATLAS):	0.3701	0.0006	---	---
Variation (+/-):	0.0242			
Wtd. Mean (SL1 ATLAS2):	0.3680	0,0010	0.4176	0.0011
Variation (+/-):	0.0022		0.0152	

Note 1: Std. Error (1 sigma):